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WALL JET ANALYSIS FOR CIRCULATION CONTROL AERODYNAMICS

PART II: ZONAL MODELING CONCEPTS FOR WALL JET/POTENTIAL FLOW COUPLING

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SUMMARY

This paper describes work currently in progress to update an existing transonic circulation control airfoil analysis method. Existing methods suffer from two deficiencies: the inability to predict the shock structure of the underexpanded supersonic jets; and the insensitivity of the calculation to small changes in the Coanda surface geometry. A method developed for the analysis of jet exhaust plumes in supersonic flow is being modified for the case of the underexpanded wall jet. In the subsonic case, the same wall jet model has been modified to include the calculation of the normal pressure gradient. This model is currently being coupled with the transonic circulation control airfoil analysis.

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T R A C O N

THEORETICAL APPROACH

- POTENTIAL FLOW
  - JAMESON'S FULL POTENTIAL METHOD

- VISCOUS FLOW
  - WALL JET REGION

    FINITE-DIFFERENCE METHOD USING AN EDDY VISCOSITY MODEL FOR CLOSURE

  - AIRFOIL UPPER SURFACE AHEAD OF SLOT AND ALL OF LOWER SURFACE

    INTEGRAL METHODS

    LAMINAR -- COHEN AND RESHOTKO

    TURBULENT -- GREEN ET AL.

Figure 2. TRACON--Component Analysis Procedures.

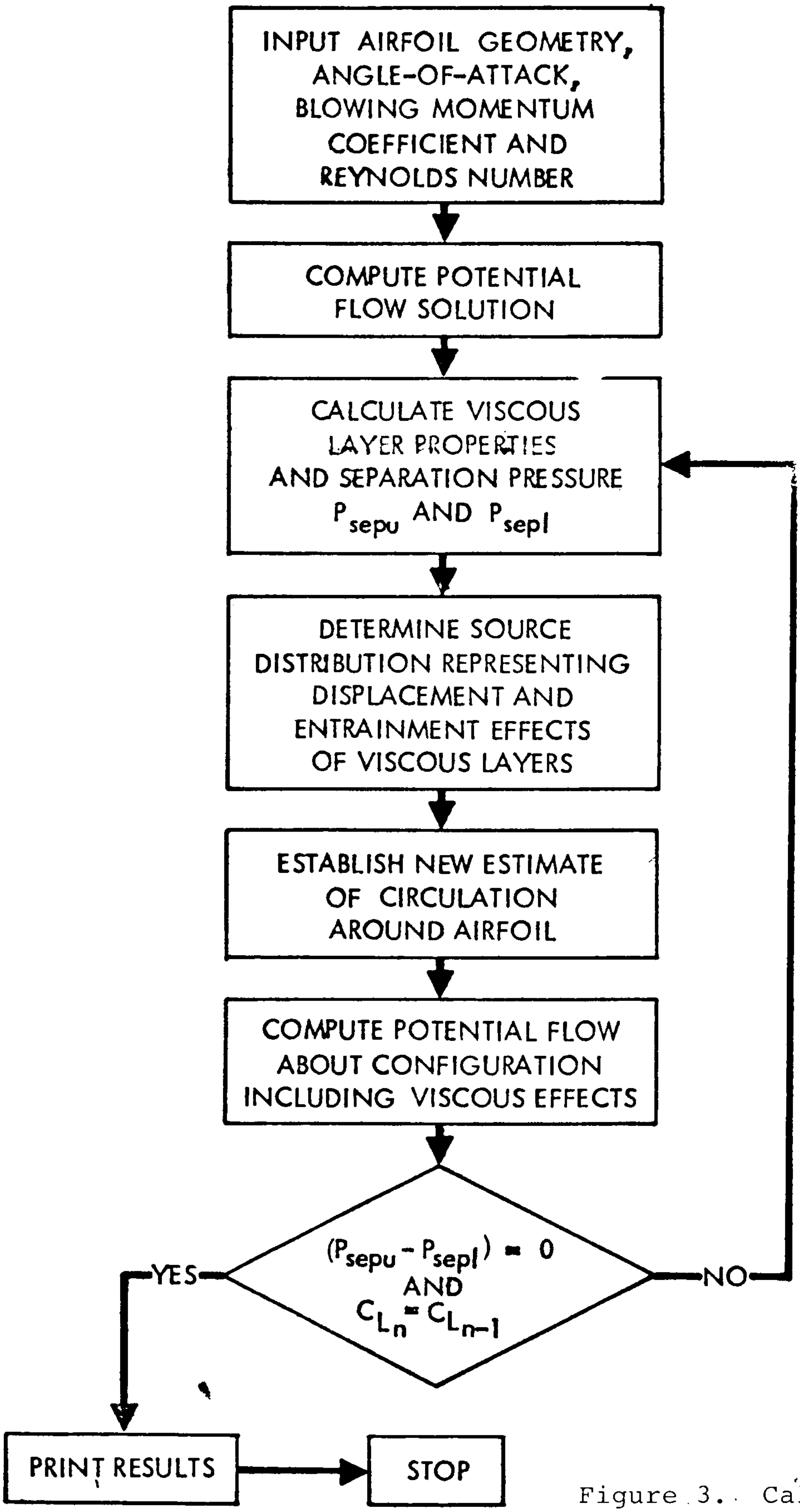


Figure 3. Calculation Procedure.

Having obtained the points of separation and corresponding static pressures for the upper and lower surfaces, a new value of circulation is estimated on the basis of separation pressures and current value of lift. A new potential flow solution can then be computed using this new estimate of circulation with the viscous effect, i.e., velocity component normal to the surface taken into account.

Convergence is checked at this stage. The calculation continues for another cycle unless P_{sepu} and P_{sepl} are in close agreement and the variation of the lift coefficient between successive iterations is in the range of convergence.

As shown in Figures 4 and 5, the basic analysis performed quite well. A relatively high Mach number case (0.6) at an angle of attack of -10° produces a strong shock wave as shown in Figure 4. The analysis accurately predicts the shock location and overall pressure distribution. Similarly in Figure 5 for a low Mach number but with blowing, the analysis again performs well in comparison with experiment. The strengths and weaknesses of TRACON are summarized in Figure 6.

3.0 CURRENT DEVELOPMENTS

The two basic objectives of the current work are as follows. (1) Formulation of the methodology to describe the inviscid flow of an underexpanded wall jet into a co-flowing stream. The method must be able to describe the supersonic flow that results from a nozzle operating choked into a stream having a free-stream Mach number in the range $0.3 \leq M \leq 0.8$. As part of this objective, procedures for coupling the wall jet calculation with the overall circulation control calculation method, TRACON, were considered. (2) Formulation of methodology to determine the effect of the Coanda jet on surface pressures. In this approach, the direct influence of the normal momentum equation is required. As with the first objective, procedures must be developed for coupling the normal pressure gradient calculation with solutions for the streamwise momentum and with the external potential flow (TRACON).

A literature survey indicated that although several researchers have investigated the flow field of supersonic jet plumes, including the underexpanded jet, only one group, from SAIC/Princeton led by Dash and co-workers (5), has considered the underexpanded <u>wall</u> jet. The shock structure of an underexpanded wall jet is physically very similar to that of a jet plume; because of this, Dash and Wolf (6) have recently modified one of their codes for application to curved wall jets. For the viscous model the finite difference, two-layer turbulence model of Dash and Beddini (7) has the required theoretical basis for application to circulation control wall jets. This analysis procedure, called SPLITWJET (hereinafter termed WJET), is completely described in (7) and (8). WJET solves a set of curvilinear, higher-

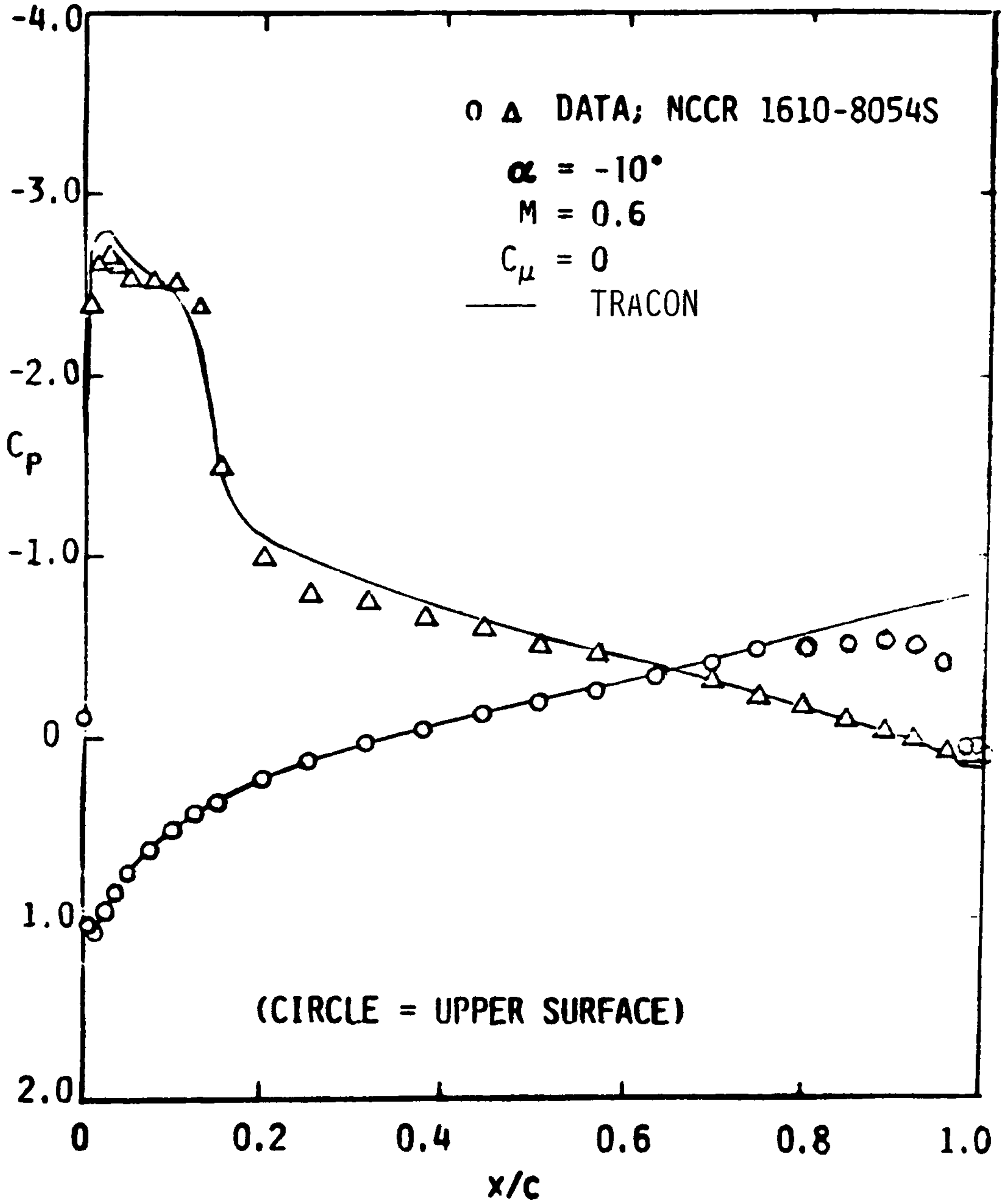


Figure 4. Comparison between Calculated and Measured Pressure Distributions; NCCR 1610-8045S.

Alpha = -0.01; C_μ = 0.0355; C_L = 2.128; C_{L_C} = 2.140

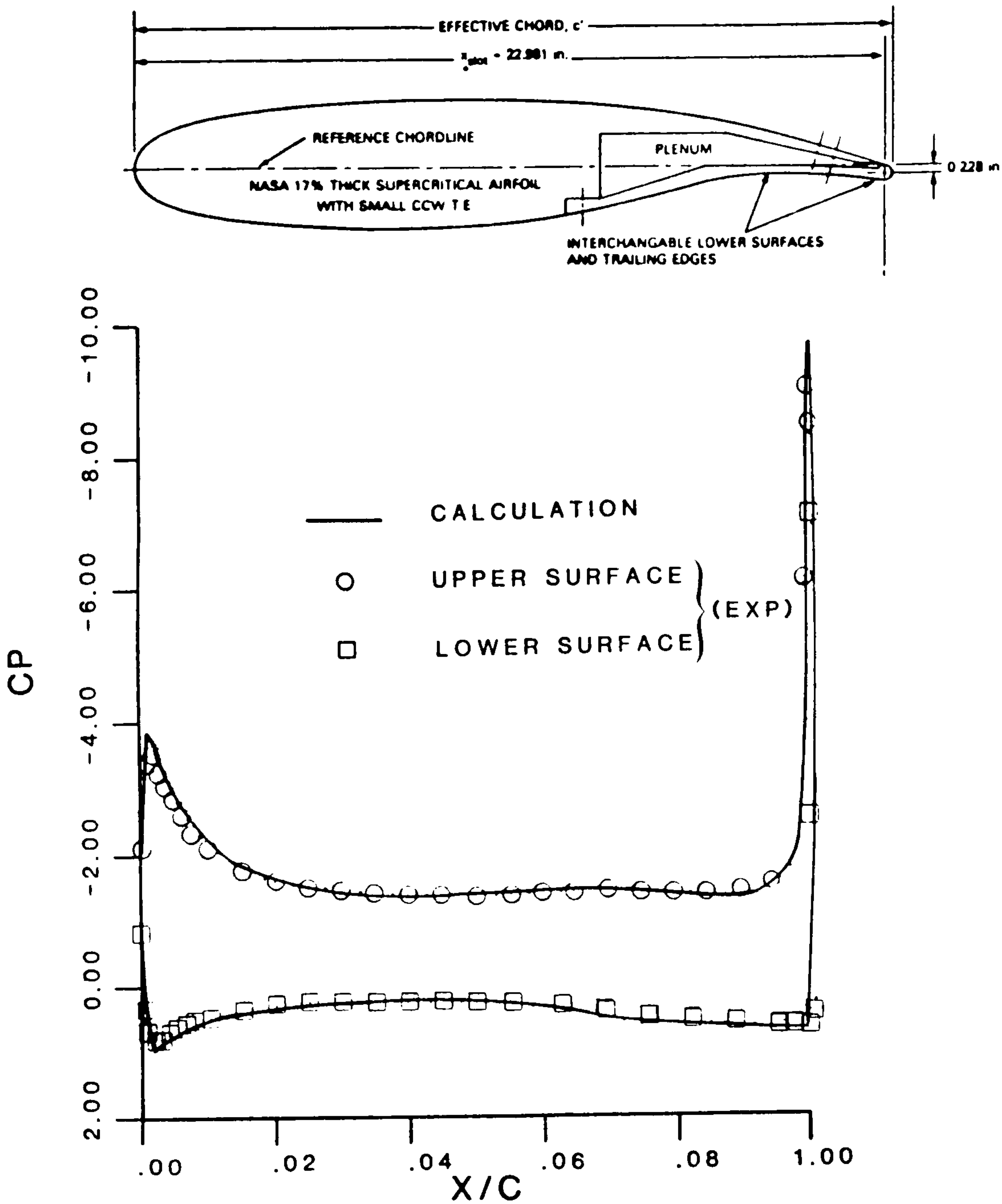


Figure 5. Comparison between Calculated and Measured Pressure Distributions; Supercritical Airfoil.

TRACON

SUMMARY

- ZERO BLOWING -- SHOCK LOCATIONS PREDICTED QUITE ACCURATELY FOR ROUNDED TRAILING-EDGE AIRFOILS

- LOW BLOWING -- PREDICTED PRESSURES AND C_L - C_μ IN GOOD AGREEMENT WITH EXPERIMENT

- HIGH BLOWING -- PREDICTED BEHAVIOR GOOD AT LOW MACH NUMBERS BUT AT HIGH MACH NUMBERS A MODEL OF THE JET SHOCK STRUCTURE IS NEEDED

- BECAUSE OF EMPIRICAL MODEL TO ACCOUNT FOR COANDA SUCTION, THE EFFECT OF SMALL CHANGES IN GEOMETRY CANNOT BE ACCOUNTED FOR IN A CONSISTENT MANNER

- DISPLACEMENT THICKNESS COUPLING BETWEEN VISCID AND INVISCID FLOWS MAY BE INADEQUATE AT HIGHER MACH NUMBERS

Figure 6. TRACON—Summary of Program Features.

order boundary layer equations employing a mapped surface--normal grid network. A key ingredient of WJET is the inclusion of a hybrid, two-layer turbulence model which couples a damped Van Driest inner mixing layer solution to a two-equation, $k\varepsilon$ outer solution, matching at the grid point corresponding to y+ ~ 50 ($y+ = n\tau_s^{\frac{1}{2}}\rho^{\frac{1}{2}}/\mu_\ell$), where n is the distance from the surface, τ_s is the wall shear stress, ρ is the density and μ_ℓ is the laminar viscosity. The turbulence model contains curvature corrections based on the work of Launder et al. (9) and Hah and Lakshminarayana (10) which are required to account for the significantly enhanced wall jet mixing rates associated with strong convex curvature. The combined system of mean flow and turbulence model equations are integrated using an efficient upwind fully implicit difference algorithm, and the jet growth is controlled by an ordinary differential equation keyed to the edge vorticity.

The inclusion of normal pressure gradient terms due to curvature in a boundary layer approach has been addressed by Mahgoub and Bradshaw (11). For the wall jet application the following approach has been developed.

1. Matching between the potential flow and the wall jet occurs at the wall jet edge.

2. The pressure variation across the wall jet is solved using the viscous normal momentum equation.

Since the inclusion of the normal momentum equation renders the wall jet equations elliptic, direct spatial marching of the complete set of wall jet equations is ill posed. The remedy involves splitting the pressure field such that:

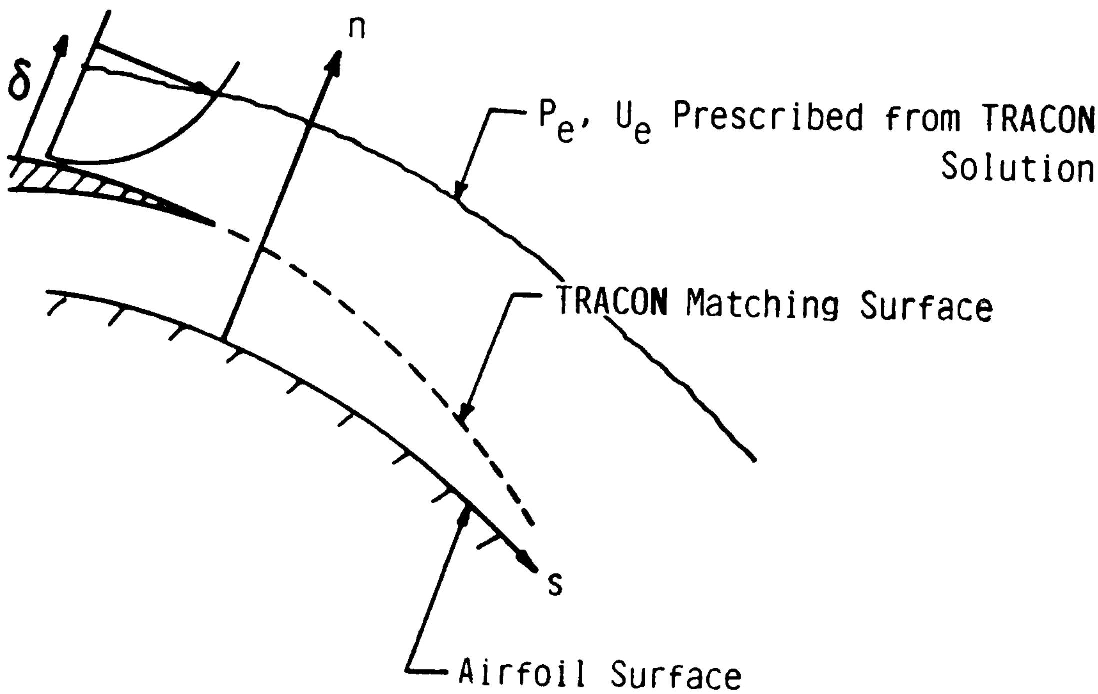
1. the wall jet equations (<u>not</u> including the normal momentum equation) are solved in a parabolic fashion with the streamwise pressure gradient determined from a globally imposed pressure field, P(s,n); and

2. a revised pressure field, $\bar{P}(s,n)$, is determined in the course of the parabolic wall jet solution using the continuity and normal momentum equations; the revised pressure field is used in local thermodynamic relations and the normal velocity distribution arrived at from the coupled continuity/normal momentum equation solution at each step is used in the convective terms of the parabolic wall jet equations.

This procedure is summarized in Figure 7.

In the subsonic case the strategy for coupling WJET with TRACON (Figure 8) is as follows:

<u>SUBSONIC WALL JET CALCULATION</u>



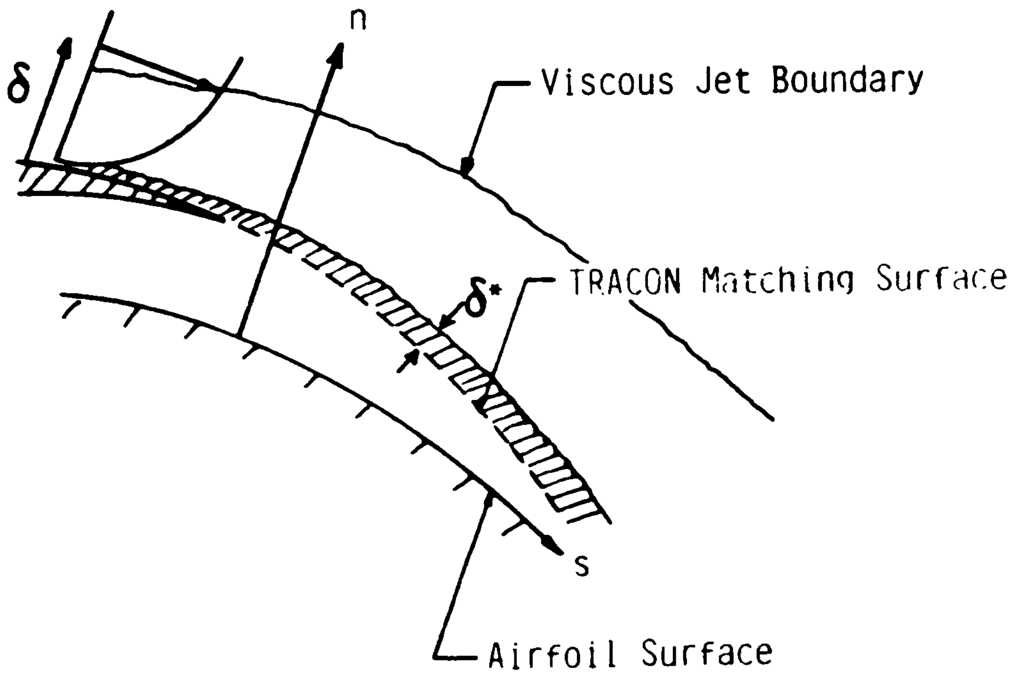
* PARABOLIC SOLUTION WITH $\partial/\partial s\left[P(\xi,\eta)\right]$ FROM POTENTIAL FLOW SOLUTION

* CROSS-FLOW SOLUTION BEGINNING AT OUTER EDGE OF WALL JET WITH BOUNDARY CONDITIONS FROM TRACON SOLUTION GIVES NEW $P(\xi,\eta)$

* SECOND ITERATION WITH $\partial/\partial s\left[P(\xi,\eta)\right]$ FROM UPDATED PRESSURE FIELD

Figure 7. Analysis Procedure for Subsonic Wall Jet.

OVERLAP COUPLING FOR A SUBSONIC WALL JET



- SOLVE POTENTIAL FLOW OVER TRACON MATCHING SURFACE WITH $\varphi_n(s)$ PRESCRIBED
- SOLVE WALL JET USING PRESSURE SPLIT PNS APPROACH
- DETERMINE $\delta^*(s)$ FOR OVERLAP REGION AND GENERATE $\varphi_n(s)$ FOR NEXT POTENTIAL FLOW SOLUTION

Figure 8. Coupling Procedure for Subsonic Wall Jet.

1. the TRACON potential flow calculation is performed utilizing a trailing-edge geometry which smoothly blends the slot lip to the airfoil trailing edge (this surface is defined as the TRACON matching surface in Figure 8; and

2. the WJET wall jet calculation is performed over the actual airfoil surface (Figure 8).

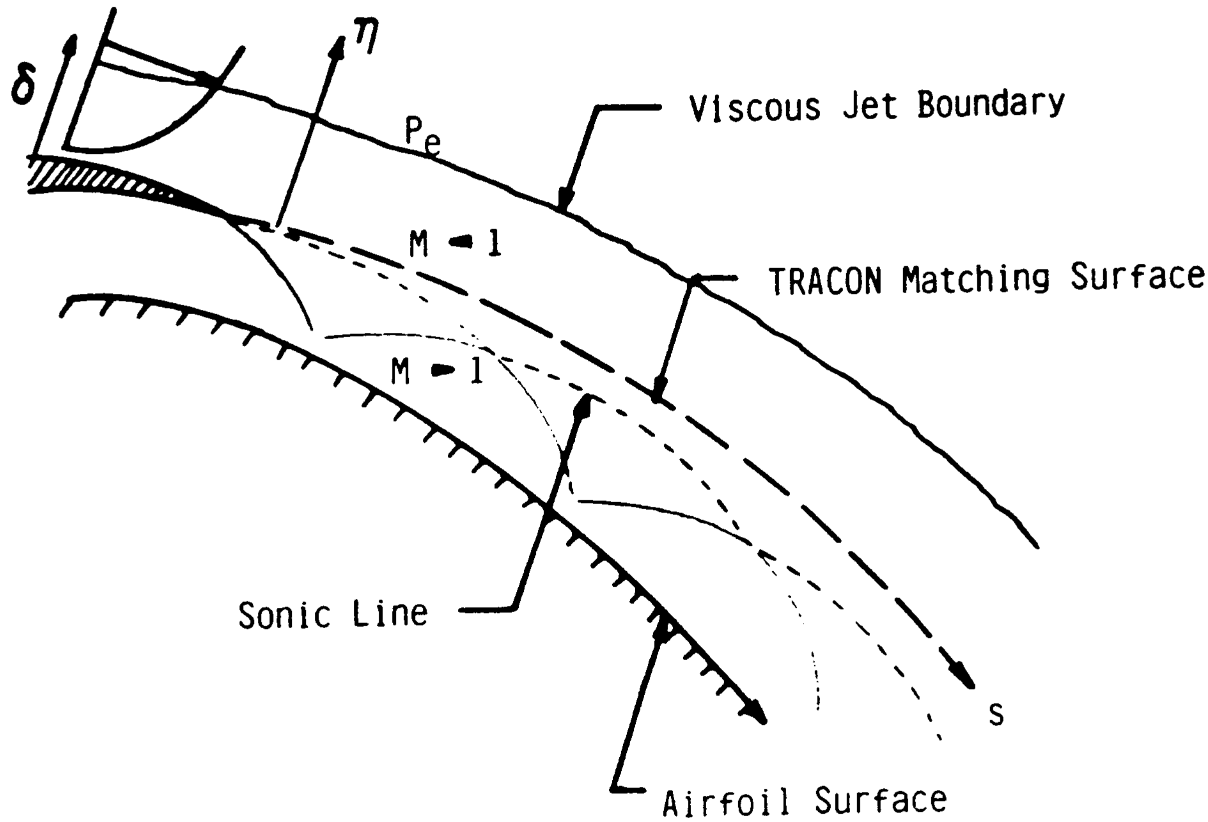
To interactively couple the two solutions, the WJET calculation requires an inviscid flow map of the TRACON calculation to obtain outer edge conditions and streamwise pressure gradients, while the TRACON calculation requires the stipulation of the source strength distribution, $\phi_n(s)$, along the TRACON matching surface. The definition of the source strength distribution in a flow with large normal pressure variations requires careful derivation of displacement thickness relations. The usual simplifying approximations employed for standard boundary layer problems cannot be employed. To date, the wall jet analysis has been coupled with TRACON and preliminary calculations are being performed to check out the program logic.

In the supersonic (underexpanded wall jet) case a similar strategy has been developed. In recent years considerable research has been carried out on the analysis of supersonic plumes. Dash and co-workers at SAIC/Princeton (12) through (14), and Wilmoth (15) of NASA Langley Research Center have developed shock capturing technology which accurately models the multi-cell embedded shock structure of underexpanded jets. Steger (16) and Diewert (17) of NASA Ames research Center, Birch of Boeing (18), Perry and Forrester (19), Shang of AFWAL (20) and Cline of Los Alamos (21) have all in recent years considered the analysis of supersonic free jets. These analyses have ranged from two-dimensional parabolized Navier-Stokes solvers to full three-dimensional time-dependent codes. The shock wave structure of an underexpanded wall jet is very similar to that of a jet plume, with one exception: the wall jet does not have the extended inviscid core region that characterises underexpanded free jets, and hence, the waves in wall jets would be propagating in a fully turbulent environment several slot heights downstream of the slot exit, see Figure 9. To properly treat this viscous problem, a parabolized Navier-Stokes formulation is required which can be directly coupled with a potential flow solution.

The basic structure for a supersonic wall jet solver already exists in WJET. In order to avoid having two separate codes to analyze subsonic and supersonic wall jets, it is more practical to develop a supersonic pressure solver for WJET. Thus, WJET will be used in its present form to solve the entire wall jet with:

1. pressures in supersonic regions determined by a characteristic based pressure solver;

SUPERSONIC WALL JET CALCULATION



- SUPERSONIC REGION -- PARABOLIC SOLUTION WITH $\partial P/\partial s$ FROM VISCOUS CHARACTERISTIC METHOD (WAVE SOLVER)

- SUBSONIC REGION -- PARABOLIC SOLUTION WITH $\partial P/\partial s$ FROM POTENTIAL FLOW SOLUTION

- SONIC LINE MATCHING AS IN FREE JET APPROACH OF DASH

- CROSS-FLOW SOLUTION IN SUBSONIC REGION WITH BOUNDARY CONDITIONS:

  $V(\eta = 0) = U(\eta = 0) \tan \theta_{CHARC.}$

  $P(\eta = 1) = P_e$

Figure 9. Analysis Procedure for Underexpanded Supersonic Wall Jet.

2. pressures in subsonic regions split with the streamwise gradient imposed from TRACON and the normal variation determined by solving the continuity and normal momentum equations; and

3. coupling procedures utilized to interface the pressures at the near wall jet and mixing layer sonic lines.

The same overlap procedure described previously will be utilized to couple the wall jet and TRACON potential flow solutions. However, the matching surface cannot be arbitrarily blended from the slot lip to the airfoil surface as if it is for the subsonic case, since it must remain above the jet mixing layer sonic line (Figure 10). The extension of the overlap approach to accommodate this modification is conceptually straightforward, but the details require significant consideration.

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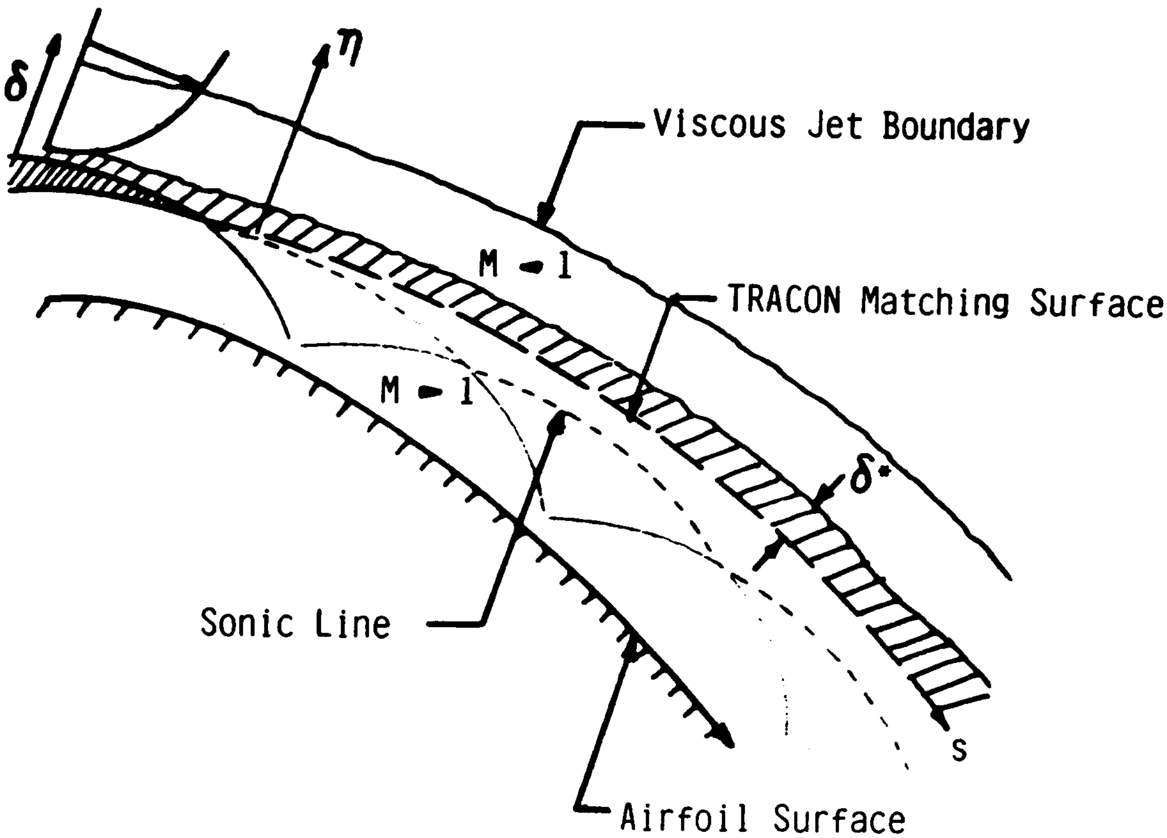
OVERLAP COUPLING FOR A SUPERSONIC WALL JET



- MATCHING SURFACE CONFIGURED TO RESIDE ABOVE SONIC LINE

- POTENTIAL FLOW OVERLAP INCLUDES ONLY SUBSONIC REGION OF JET

- P(s) -- SUPERSONIC ($\eta < 0$) -- WAKE SOLVER
  -- SUBSONIC ($\eta > 0$) -- PRESSURE SPLIT

- δ^*(s) DETERMINED FOR SUBSONIC PORTION OF JET -- INCLUDES INFLUENCE OF JET UNDEREXPANSION

Figure 10. Coupling Procedure for Underexpanded Supersonic Wall Jet.

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